

Reflection Spectra from Photoionized Accretion Discs

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Abstract. We review recent progress on the modeling and use of reflection spectra from irradiated and ionized accretion discs. On the computational side, calculations of reflection spectra from discs with non-uniform density structure have shown that thermal instabilities can effect the predictions. Ionized reflection spectra have been used effectively in fitting data of Narrow-Line Seyfert 1 galaxies, and have placed constraints on the strength and shape of soft X-ray emission lines.

1. Introduction

With the discovery of Fe K α emission at 6.4 keV and spectral hardening at 20–30 keV in the X-ray spectra of Seyfert 1 galaxies (Pounds et al. 1990), it was realized that there is a significant amount of reprocessing material in the vicinity of the X-ray source. This material must be optically thick to electron scattering and relatively ‘cold’ (as compared to the X-ray emitting plasma). The observation of the relativistically broadened Fe K α line in MCG–6-30-15 by Tanaka et al. (1995) confirmed that, at least in some Seyfert 1 galaxies, the reflecting material was the inner part of the accretion disc. Therefore, the possibility arises of unraveling some of the mysteries of AGN accretion flows, such as its geometry, by studying the reflection signatures in X-ray spectra.

2. Constant density models

Numerical models of reflection spectra from accretion discs began with the simplest case: assuming a static, neutral and constant density slab of material irradiated by a power-law continuum of X-rays. George & Fabian (1991) and Matt, Perola & Piro (1991) performed Monte-Carlo calculations of the reflection spectra in such circumstances, and provided predictions on the equivalent width (EW) of Fe K α for different reflection geometries.

Of course, assuming that the gas remains neutral while it is being bombarded by X-rays is not very satisfying, and this led Ross & Fabian (1993) to model photoionized reflectors (see also Życki et al. 1994). As might easily be

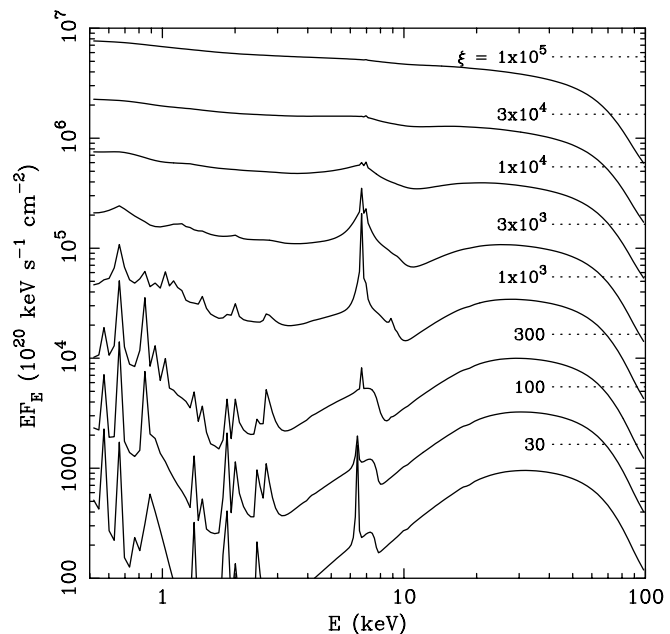


Fig. 1. Reflection spectra (solid lines) from constant density slabs illuminated by a power-law continuum of X-rays with photon-index $\Gamma = 2$ (dashed lines). The ionization parameter ξ of the reflector increases from 30 to 10^5 going from bottom to top in the plot. Taken from Ross, Fabian & Young (1999).

imagined, allowing the gas to be ionized changes significantly the types of features imprinted on the X-ray reflection spectrum. This is illustrated in Figure 1 taken from the paper by Ross, Fabian & Young (1999) where extensive calculations are presented. Here we see X-ray reflection spectra for different cases of the ionization parameter $\xi = 4\pi F_X / n_H$ where F_X is the total flux incident on the slab and n_H is the hydrogen number density of the gas. In every case the reflector is irradiated by a power-law continuum with photon-index $\Gamma = 2$ (denoted by the dotted lines in Fig. 1). When the ionization parameter is small the gas is weakly ionized and there is a large amount of photoelectric absorption by metals between 0.1 and 20 keV. This absorbed energy is thermalized by the gas and re-radiated in the soft X-rays and extreme-UV wavebands (not shown in Fig. 1). The same transitions which can

absorb X-ray photons can also emit them, so the recombination and fluorescent lines of the abundant metals also occur between 0.1 and 20 keV. Due to its relatively high cosmic abundance and large fluorescent yield the Fe $K\alpha$ line at 6.4 keV is the most prominent of these lines. Above ~ 20 keV electron scattering results in the albedo of the reflector to approach unity, until above ~ 50 keV where electron recoil causes it to decrease again.

Increasing the ionization parameter of the slab removes the ability of the gas to absorb the X-ray photons, and so increases the albedo of the reflector. This occurs first at lower energies and then moves to higher energies as the gas becomes more ionized. Therefore, the Fe $K\alpha$ line is a strong feature in the reflection spectrum over more than three orders of magnitude in ionization parameter. The line does shift energy, however, from 6.4 keV when Fe is only weakly ionized to 6.7 keV when Fe is helium-like, having a significant impact on its observed strength (Matt, Fabian & Ross 1993, 1996). One other important effect of a larger ionization parameter is the broadening of the spectral features by Compton scattering (this can be especially seen in the $\xi = 3 \times 10^3$ model in Fig. 1).

Constant density reflection models such as the ones shown in Figure 1 are useful because their properties are easily parameterized by only two parameters (ξ & Γ). They have also been widely used to study the response of the reflection spectrum and the Fe $K\alpha$ line to changes in metal abundance (Matt, Fabian & Reynolds 1997; Ballantyne, Fabian & Ross 2002), and inclination angle (Ghisellini, Haardt & Matt 1994).

3. Non-uniform density models

Although a constant density accretion disc does have some theoretical justification (a standard thin radiation-pressure dominated accretion disc has a roughly constant vertical density profile; Shakura & Sunyaev 1973), the material on the irradiated surface is not in pressure equilibrium if the density is held fixed. Ross et al. (1999) computed the reflection spectrum from a disc where the density followed a Gaussian drop-off. The resulting spectrum exhibited much weaker reflection features than the equivalent constant density model.

The next step in non-uniform density models was to enforce the condition of hydrostatic equilibrium on the illuminated gas. Initial investigations on the disc structure of illuminated hydrostatic discs were done by Róžańska & Czerny (1996) and Róžańska (1999). The full radiative transfer and photoionization problem was then performed by Nayakshin, Kazanas & Kallman (2000) and subsequently investigated in a series of papers (Nayakshin & Kallman 2001; Nayakshin & Kazanas 2002). These calculations found that in many cases the illuminated gas structure took up a two-phase appearance with a hot ($\sim 10^7$ K), ionized zone on the surface and a colder ($\sim 10^5$ K), recombined zone deeper in the atmosphere. The two zones would

be in pressure balance with each other and the transition between them could be very sharp due to the thermal ionization instability (e.g., Krolik, McKee & Tarter 1981). In this case, the reflection spectrum would appear to be a diluted form of a neutral reflector as all of the emission lines would arise from the cold recombined zone and then are scattered as they pass through the outer hot ionized skin. Therefore a neutral Fe $K\alpha$ line at 6.4 keV would be expected even when the disc is highly illuminated.

The sharpness of the temperature drop between the two zones has a great impact on the features in the reflection spectrum. Ballantyne, Ross & Fabian (2001) and Ballantyne & Ross (2002) present a series of hydrostatic calculations which show reflection spectra with strong ionized Fe $K\alpha$ lines. The nearly discontinuous drop in temperature, indicative of the thermal ionization instability, seems to only occur when the Compton temperature of the illuminated gas is a few keV (see Figure 2). However, these considerations are subject to uncertainties in the illuminating radiation field, particularly the high-energy cutoff of the incident power-law (Ballantyne & Ross 2002), and also in the true structure of the surface of accretion discs. The question of how important is the thermal ionization instability in determining the reflection spectra is still one that requires more research.

While it is possible to fit X-ray data with hydrostatic models (Nayakshin's models are available in XSPEC), they are subject to a large number of assumptions on the accretion disc structure, and it is this author's opinion that the constant density models are more useful in fitting AGN data. One of the problems is that in order to calculate a hydrostatic model, the height of the accretion disc at the irradiated point must be known. This requires assuming a black hole mass, accretion rate, a radius, and a full disc model before the calculation can proceed. Therefore, these models may be more useful in fitting data from Galactic black hole candidates where there are often independent estimates of at least some of these parameters.

4. Comparison with data

Recently, the sophisticated reflection models discussed above have been applied to the data. This section discusses two very different uses of the ionized constant density models.

Ballantyne, Iwasawa & Fabian (2001) fitted *ASCA* data of five Narrow-Line Seyfert 1 (NLS1) galaxies with the models of Ross & Fabian (1993). NLS1s are thought to be systems in which a smaller than 'normal' black hole (say, $10^6 M_\odot$) is accreting at a high fraction of its Eddington rate (Pounds, Done & Osborne 1995; Boller, Brandt & Fink 1996). In such a situation it is expected that the disc would be hot and ionized. Observations of many NLS1s have provided some evidence for this (Comastri et al. 1998, 2001; Turner, George & Nandra 1998, Vaughan et al. 1999, Turner et al. 2001a,b), but this hypothesis needed to be

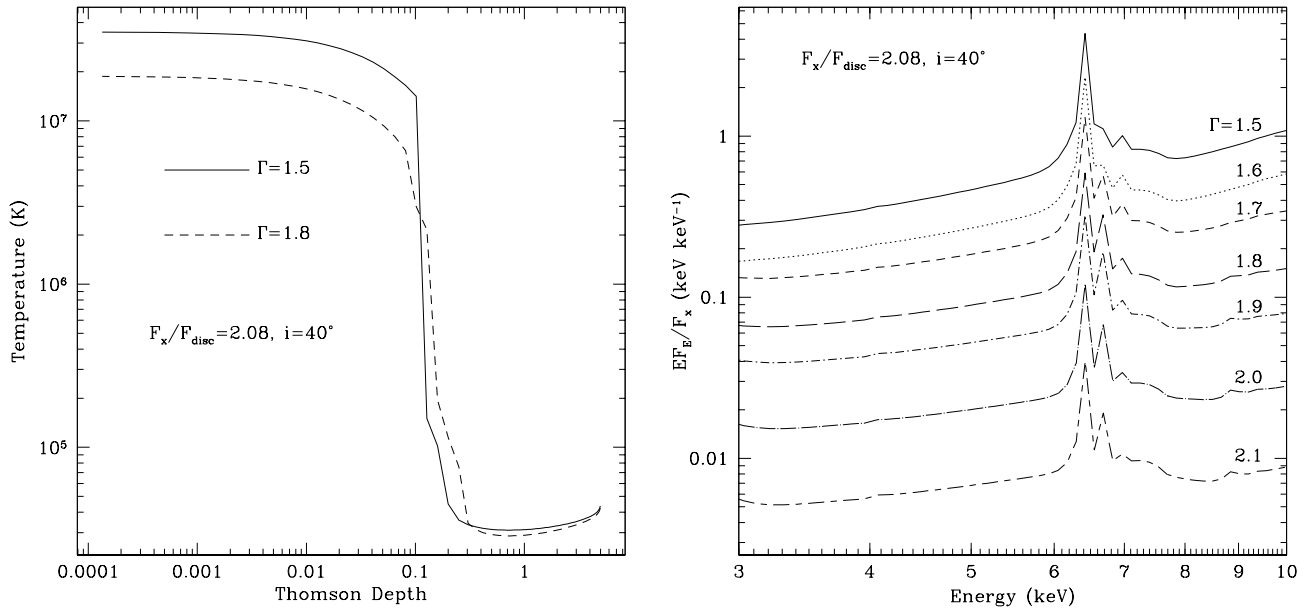


Fig. 2. The left panel shows the temperature structure of the illuminated atmosphere taken from two models presented by Ballantyne & Ross (2002). The sharp temperature transition occurs for the $\Gamma = 1.5$ model, but not for the $\Gamma = 1.8$ model which has a lower surface temperature. The corresponding Fe K α lines are shown in the right-hand panel. The $\Gamma = 1.5$ model exhibits a strong neutral Fe K α line, while the $\Gamma = 1.8$ spectrum also shows a line from He-like Fe at 6.7 keV. In this panel, the spectra are vertically offset for clarity. All the models assumed a black hole mass of $10^8 M_\odot$, an accretion rate of 0.1% of Eddington, and that the reflection occurred at 7 Schwarzschild radii from the black hole. The illuminating flux was 2.08 times the disc flux and was incident at an angle of 40 deg from the normal.

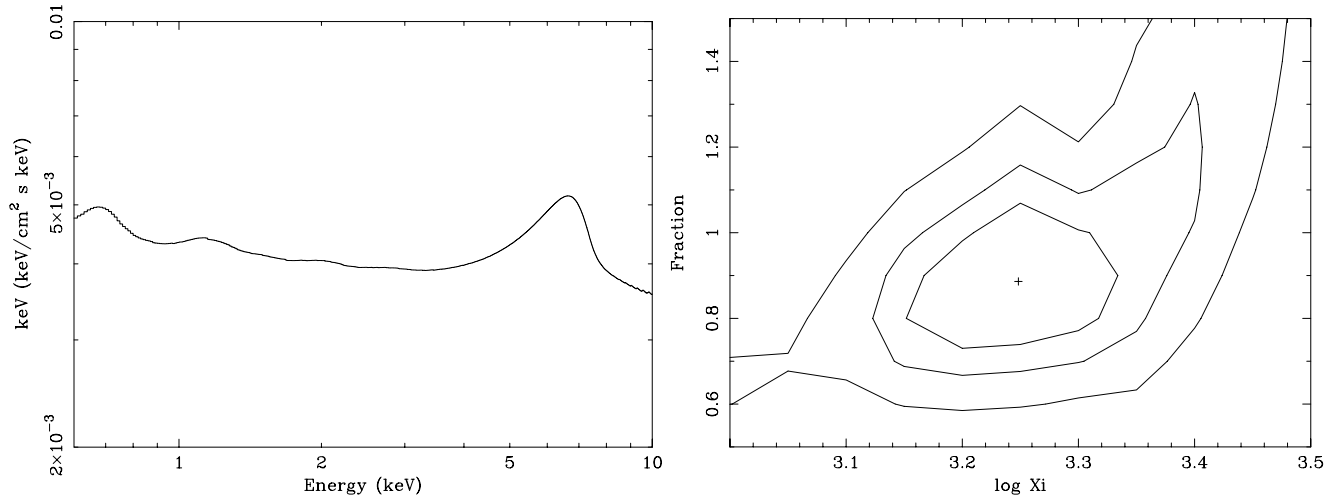


Fig. 3. The left hand panel shows the relativistically blurred ionized disc model fitted to the *ASCA* spectrum of the NLS1 Mrk 335. The right-hand panel shows confidence contours in the $\log \xi$ -reflection fraction plane. This NLS1 requires an ionized reflector with strong emission from a He-like Fe K α line at 6.7 keV. Taken from Ballantyne, Iwasawa & Fabian (2001).

tested with self-consistent models. Ballantyne et al. (2001) found that four out of the five NLS1 considered were well fit by the ionized reflection models (Fig. 3), a stronger constraint than measuring the energy of the Fe K α line because the continuum is fit simultaneously with the line.

Recent *XMM-Newton* observations of MCG-6-30-15 and Mrk 766 by Branduardi-Raymont et al. (2001) sug-

gested that there were strong relativistic emission lines from C, N and O in the soft X-ray part of the spectrum. Ionized reflection models can provide predictions on the strength of such lines as they are predicted along with Fe K α and the reflection continuum. Ballantyne & Fabian (2001) fit the *ASCA* data of MCG-6-30-15 around the Fe K α line with both constant density and hydrostatic re-

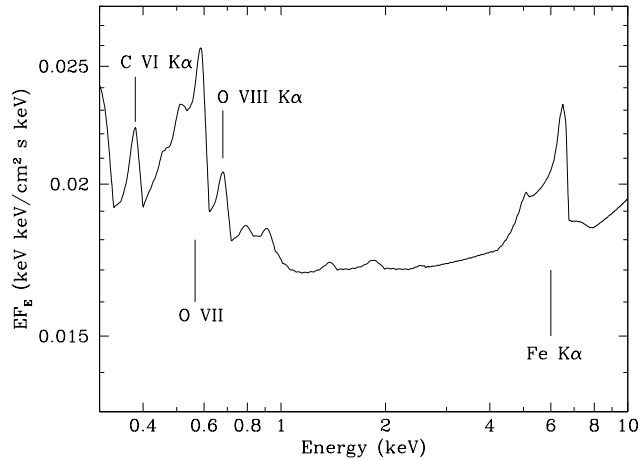


Fig. 4. This plot shows the best fit constant density reflection model determined from fitting the 1994 *ASCA* data of MCG-6-30-15 above 3 keV. The prominent emission lines are indicated. The model predicts that the O VIII emission line will have an EW of only 5.4 eV. From Ballantyne & Fabian (2001).

flection models. The models then predicted the strength and shape of the carbon and oxygen lines (see Fig. 4). Both types of models predicted that the EWs of the soft X-ray lines should be on the order of tens of eV, and that O VII and Fe L emission should both be common in the soft X-ray band. These results raise questions about the relativistic diskline interpretation of Branduardi-Raymont et al. (2001).

The current most common reflection models in use in XSPEC are PEXRAV for neutral reflection and PEXRIV for ionized reflection (Magdziarz & Zdziarski 1995). Both are constant density models, and both calculate the reflection continuum, including edges. This means that emission lines, such as Fe K α must be added in separately to the model which is not an ideal situation because, as Fig. 1 shows, the properties of the line are closely linked with the reflection continuum. For ionized reflection, PEXRIV suffers from inaccuracies at high ionization parameters because it neglects Comptonization (see Fig. 7 in Ross et al. 1999). A better alternative for comparing reflection models to data is to use the constant density ones computed using the code of Ross & Fabian (1993). Two grids of these models (one with solar Fe abundance, the other at twice solar Fe) are now available for public use as XSPEC table models¹. The grids cover a wide range of parameter space ($1.0 \leq \log \xi \leq 6.0$, $1.5 \leq \Gamma \leq 3.0$, $0.0 \leq R \leq 2$, where R is the reflection fraction: $\text{total} = R \times \text{reflected} + \text{incident}$) and of course include many emission lines computed self-consistently with the reflection continuum.

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